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DETERMINATION OF MECHANICAL PROPERTIES OF METHYL METHACRYLATE ADHESIVE (MMA)

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Abstract

Experimental testing of epoxy adhesives, which are commonly used in civil engineering for the strengthening of existing structures with composite products have been a topic of limited studies. It was due to the damage which usually occurred not in the adhesive layer but in the strengthened material. Recent studies have shown that the choice of an adhesive significantly affects the load-bearing capacity of the entire joint. The paper presents the results of strength tests of a selected methyl methacrylate adhesive, carried out according to the standards EN ISO 527-1 and EN ISO 527-2. Comparing the results to the data provided by the manufacturer (tested in accordance with ASTM D638) discrepancies have been found in the normative assumptions and consequently differences in the results. Experiments on the adhesive showed clear dependency on the speed of testing which revealed through variable characteristics after the elastic limit. Numerical simulations were also carried out assuming the elastic-plastic material model. The analyses allowed to obtain the distribution of stresses and deformations along the length of the sample and allowed to verify the length of the extensometer used. Comparison of results obtained for different measuring lengths of chosen adhesive confirmed the need to use extensometers in the testing of mechanical properties.

Keywords: **Methacrylate; MMA; Mechanical properties; Influence of test speed.**

1. INTRODUCTION AND MOTIVATION

Assessment of connections in building constructions involves an assumption that the weakest component governs the load-bearing capacity of the joints. Strengthening of existing structures requires in many cases the use of metallic fasteners such as bolts or welds. However, increasing the load-bearing capacity of building elements with Fiber Reinforced Polymers (FRP) composites requires the use of structural adhesives. For strengthening reinforced concrete (RC), masonry and timber structures with FRP composites bonded with structural adhesives, it is not necessary to analyse in details the characteristics of the adhesive or the composites, because the damage usually occurs in the strengthened material [1-4]. For this type of joints, epoxy adhesives have been successfully used [5]. Epoxy adhesives are commonly used for strengthening steel structures with carbon fiber strips or steel plates [6-8] of which the main purpose is to increase the cross-sections of the elements. In these cases the damage is usually observed in the adhesive layer, which makes a determination of mechanical properties of the bonding material necessary.

Epoxy adhesives are highly rigid and show relatively low plastic deformations at failure. Thus from a safety point of view, these adhesives do not seem to be the right choice, because the failure occurs in a sudden, brittle manner. In addition, due to the high stiffness, significant stress concentrations occur at the edges of shear connections and these zones are the failure initiation areas [9]. Common failures of adhesive layers due to the stress concentrations in joints of strengthened RC and masonry structures showed the need for research on the influence of adhesive stiffness on the load-bearing capacity of the strengthened elements [1, 10]. Although many studies have been performed, further studies of this phenomenon are necessary due to the new adhesive materials available on the market.

Double-lap tensile tests were performed for steel plates bonded with Carbon Fiber Reinforced Polymer (CFRP) laminates using different adhesives [11-13]. Despite the fact that similar values of the tensile and shear strength of the adhesives much higher load-bearing capacity was obtained with methyl methacrylate adhesives (MMA). It was mainly due to the lower stiffness compared to epoxy adhesives which causes that on the edges of the adhesive layer no shear stress concentrations occurred. Instead, the stresses are distributed on a larger area of the bond connection. The most favourable results were obtained for PLEXUS MA420 methyl methacrylate adhesive, which is analysed in this paper. This adhesive combines the high strength of epoxies and the durability of polyurethane adhesives. An important advantage is its easy application process and the short curing time. At room temperature, full strength is achieved within ~20–50 minutes, while for epoxies, this may take up to several hours [14-16].

A potential application of MMA in constructions in the European Union must be preceded by a determination of material properties according to European standards. The purpose of the work was to determine the mechanical parameters of the selected MMA with respect to ISO standards [17, 18]. An objective of this study was also to compare the obtained results to ASTM standard [16] according to which the results provided by the manufacturer were carried out. In addition, a comparative numerical analysis was performed with the assumption of an elastic-plastic material model for the adhesive.

2. MATERIALS AND RESEARCH METHODOLOGY

2.1. Laboratory tests

In this study, a methyl methacrylate adhesive PLEXUS MA420 was investigated. Tab. 2. presents the basic mechanical properties provided by the manufacturer [19]. These values were determined according to ASTM D638 [16].

In the current study, a series of quasi-static tensile tests was performed on dog-bone shape samples according to [17, 18], see Fig. 1. The tests were carried out in a hydraulic displacement controlled uniaxial testing machine. The samples were fixed in custom made aluminium clamps with a base grip length of 42.5 mm. Five repetitions were performed at speed of testing: 1 and 10 mm/min as described in section 3.1. A pair of extensometers were mounted on both sides of the specimens to measure deformations in a direction parallel to the axis of the testing machine, see Fig. 2. The extensometers' base length was 50 mm.

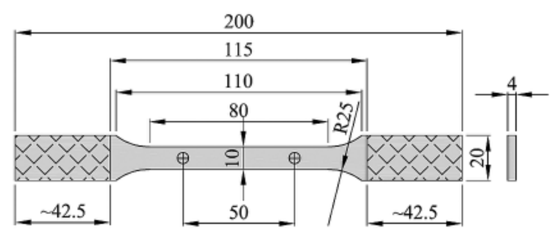

Figure 1.
The geometry of specimens according to [18]

Figure 2.
Test set-up – determination of tensile strength and stiffness

Figure 3.
Test set-up – determination of Poisson's ratio

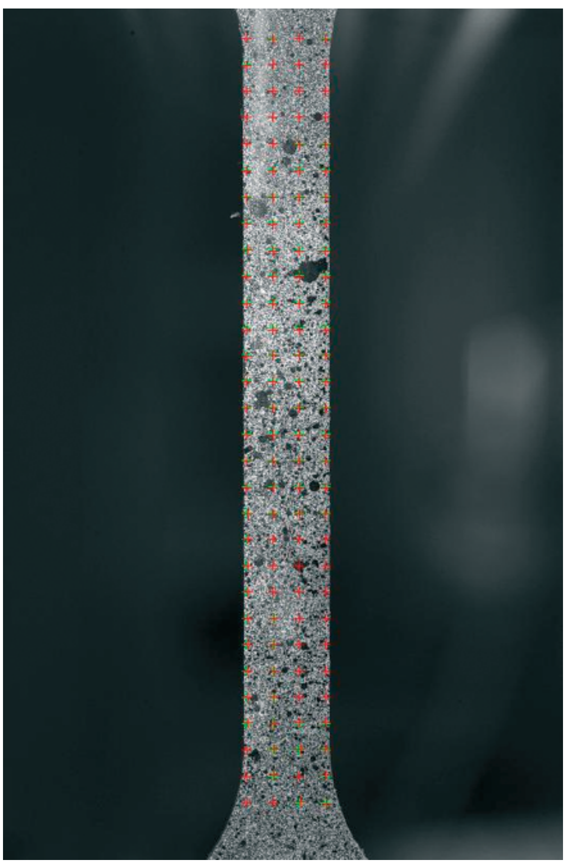

Figure 4.
Characteristic points on the narrow part of the specimen

In addition, three tensile tests were carried out with the same type of specimen to determine Poisson's ratio according to [17, 18]. The set-up is shown in Fig. 3. To measure strains in the specimens, characteristic points (speckle pattern) were applied with black and white spray paint before testing, see Fig. 4. Strains in two directions were measured with a high resolution camera and evaluated as changes in distances between the characteristic points. Then, Poisson's ratio was calculated as a ratio of these strains. A zone in the central part of the narrowed specimens was chosen for averaging the results. The tests were performed at the speed of 1 mm/min as described in section 3.1. According to [17] Poisson's ratio must be determined in the range of elastic strains, for a linear stress-strain relationship: 0.3%–ε_y. For the analysed adhesive this range was ~1.5–5%.

2.2. Numerical analyses

Numerical analyses were performed using the Finite Element Method (FEM) in ABAQUS software [20]. An elastic-plastic material model was used for the characterization of the behaviour of the adhesive, see Fig. 5. The mechanical properties of the adhesive were based on the results of the experimental studies. The values of the elastic-plastic material model are summarized in Tab. 1. In the numerical simulations, the secant modulus of elasticity was used with the characteristic points, such as the elastic stress limit σ_e and plastic stress limit σ_p with corresponding strains. Numerical analyses were carried out in a plane-stress state with dog-bone shape samples with dimensions as shown in Fig. 1. Four-node 2×2 mm finite elements were used for the wider part of the specimen and 1×1 mm elements in the narrow part of the sample. Simplified boundary conditions were assigned to reflect the constraints in the experimental studies, see Fig. 6.

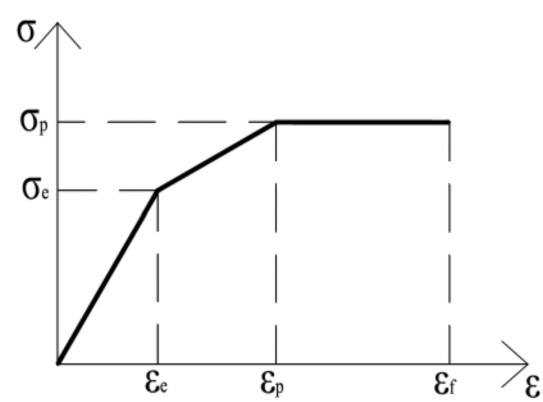

Figure 5.
Characteristic points of the material model

Figure 6.
A numerical model with boundary conditions [18]

Table 1.
Material parameters used in numerical analyses

Speed of testing mm/min	σ_e MPa	ε_e %	σ_p MPa	ε_p %	ε_f %
1	8.00	0.83	14.65	3.80	8.30
10	11.00	1.15	16.20	3.10	7.10

3. RESULTS

3.1. Laboratory tests

Tab. 2. and Fig. 6. show the results of the experimental studies. Based on the stress-strain relationships (Fig. 7.) obtained from the tensile tests the elastic modulus was calculated in the strain range of 0.05%-0.25%, according to [17]. Average tensile strength and ultimate strain of tested MMA samples at the speed of testing of 1 mm/min were 14.7 MPa and 4.11%, respectively. The corresponding modulus of elasticity was 1058 MPa. For the higher speed of testing at 10 mm/min, the values were 16.2 MPa, 6.81% and 1131 MPa, respectively. The observed differences of approximately 10% and 20% in tensile strength and stiffness clearly show the viscoelastic nature of the material.

The values obtained from the current experimental campaign differ significantly from the values given by the manufacturer, see Tab. 2. This is probably due to the discrepancies between the ISO and ASTM standards [16-18]. As an example, according to [17] the testing strain rate should cause the failure of a sample within 30 to 300s, whereas the standard [17] specifies that the test should be carried out with the speed rate that results in approximately 1% increase of longitudinal strains of the sample per minute. A crosshead displacement of the machine at the speed of 1 mm/min gives the strain rate of approximately 0.8%/min, but the duration of the test is more than 500s. A speed of testing of 10 mm/min results in the strain rate of 5%/min and failure occurs after 120s. It is therefore difficult to fulfil the entries of ISO and ASTM standards. In addition, as has been shown in Tab. 2., the speed range influences the tensile strength of the adhesive. The differences in tensile strength indicate that the samples tested by the manufacturer were probably tested at a higher strain rate. The behaviour of the adhesive indicates that

Table 2.
Summary of material parameters of the analyzed adhesive

Speed of testing mm/min	No.	Tensile strength, σ_p MPa	Strain related to tensile strength, ε_p %	Strain at failure, ε_f %	Modulus of elasticity, E MPa	Poisson's ratio, μ
Technical Data Sheet [19]						
Unknown		18.6÷20.7	-	30÷50	517÷689	0.41
Current tests data						
1	1	-	-	-	-	0.363
	2	-	-	-	-	0.344
	3	-	-	-	-	0.387
	4	15.24	3.90	5.71	1125	-
	5	15.06	4.69	10.01	1077	-
	6	13.51	3.73	9.50	938	-
	7	14.85	4.07	10.36	1074	-
	8	14.85	4.15	6.17	1075	-
Average		14.70	4.11	8.35	1058	0.365
Stand. Deviation		0.61	0.32	1.99	62.9	0.018
Coeff. of variation		4.15%	7.79%	23.83%	5.95%	4.93%
10	9	16.58	3.25	9.83	1141	-
	10	16.66	3.11	5.79	1137	-
	11	16.64	3.22	5.35	1161	-
	12	15.42	3.08	4.80	1128	-
	13	15.73	3.37	8.28	1090	-
Average		16.21	3.21	6.81	1131	-
Stand. Deviation		0.53	0.10	1.92	23.3	-
Coeff. of variation		3.27%	3.12%	28.19%	2.06%	-

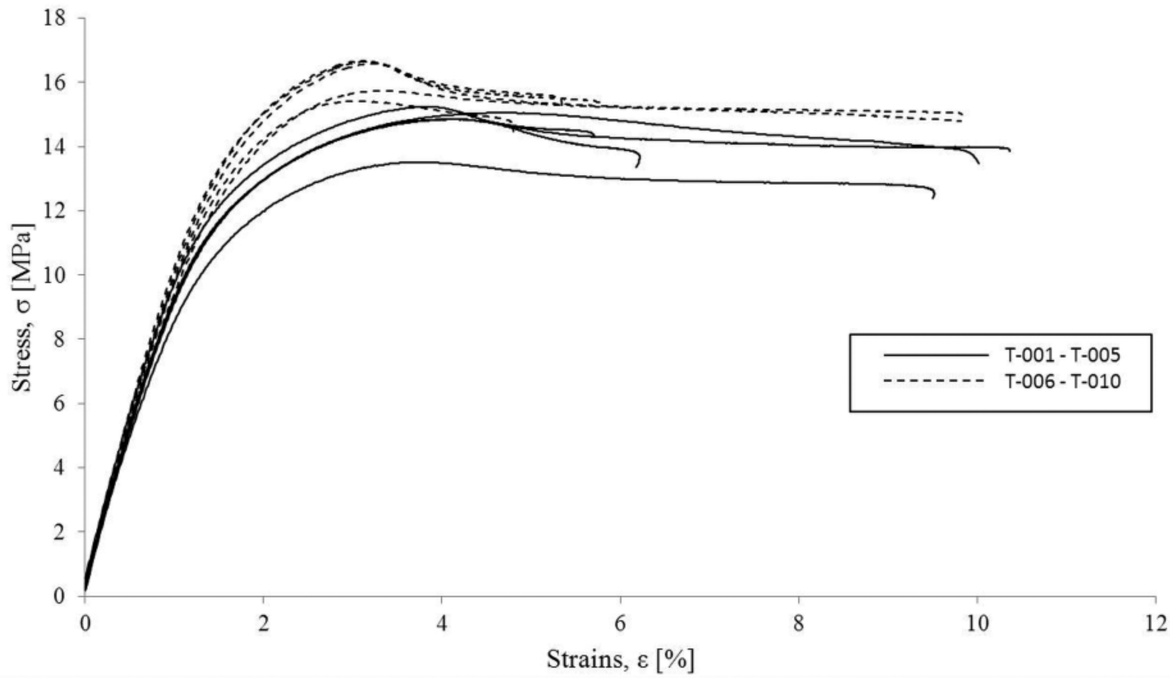

Figure 7.
Stress-strain relationships for all samples

under higher strain rate the material shows greater strength and lower plastic deformations.

Determination of modulus of elasticity was based on the linear stress-strain relationships, however, in the case of adhesives with non-linear characteristics, it should involve lower levels of stress [16]. The standard [17], however, gives a fixed strain range (0.05%–0.25%), in which the modulus of elasticity should be determined. The value of modulus of elasticity, given by the manufacturer [19], is much lower in comparison to the experimental studies, see Tab. 2. There may be several reasons causing the differences in the results. First, the geometry of a specimen may significantly affect the results. As stated in [18], results obtained for large (types 1A and 1B) and small (types 1BA, 1BB, 5A, and 5B) specimens cannot be compared with each other due to the complexity resulting from the small measurement lengths and short test time. Probably, the data provided by the manufacturer was obtained for smaller samples (type IV according to [16]) and hence observed differences. With the samples type 1BA and 1BB [18] or IV [14] there is also a risk that in case of performing tests without extensometers, higher strain values may be obtained. It is due to the fact that the strain based on the crosshead displacement is larger than the strain measured by extensometers. The differences in the results of the strain at failure are probably due to these reasons.

Fig. 8. shows the variation of Poisson's ratio with longitudinal strain obtained from three samples tested in tension. Due to the viscoelastic nature of the material, a nonlinear dependence of Poisson’s ratio was obtained. The average Poisson's ratio at speed of 1 mm/min was 0.365. The results for all samples are given in Tab. 2. The difference between the results obtained in the tests and those declared by the manufacturer is probably due to the entries in ISO and ASTM standards that regarding the determination of Poisson’s ratio differ significantly. Standard [16] indicates that the test should be carried out at the speed of 5 mm/min, but the investigation has shown that the optimum speed for the considered adhesive tests was 1 mm/min [17].

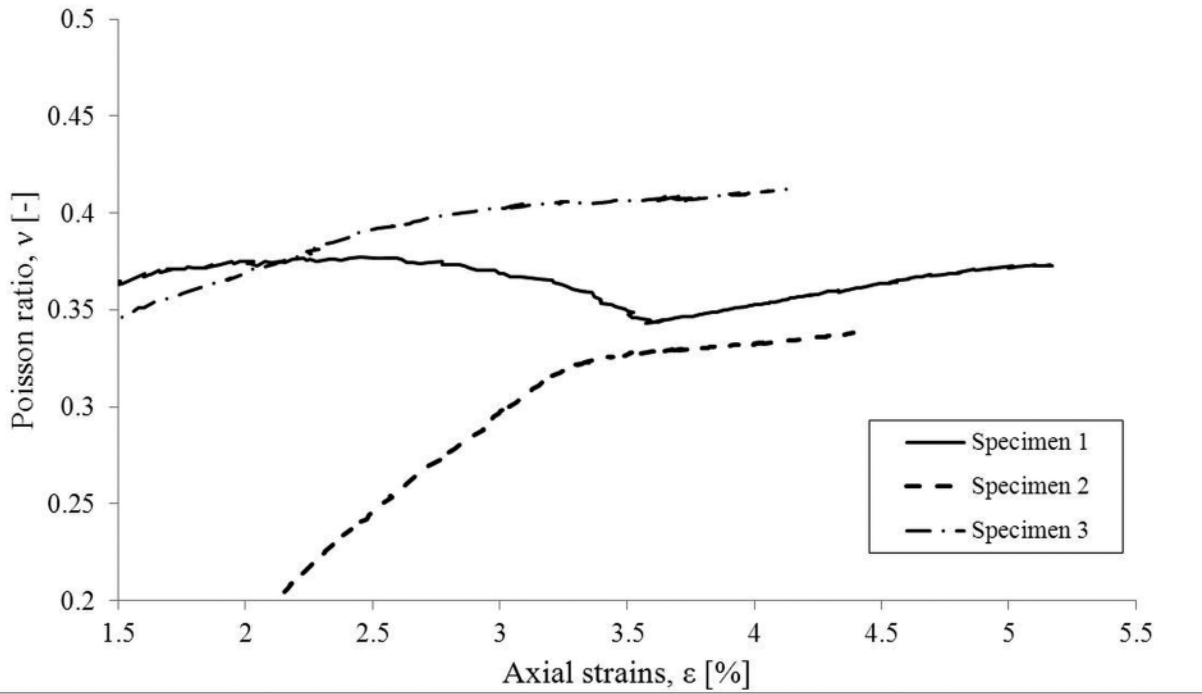

Figure 8.
Variation of Poisson's ratio with longitudinal strain

3.2. Numerical analyses

The purpose of the numerical analyses was to investigate the distribution of stresses and strains over the length of the sample and verify whether an elastic-plastic material model can be applied for modelling the behaviour of the samples subjected to tension observed during experiments.

The diagrams shown in Fig. 10. and 11. provide the distribution of engineer stresses and longitudinal deformations in the sample along the symmetry line. The different area of the cross-section of the sample close to supports and at the narrow part cause non-linear stress profile. In addition, a local disturbance of stress at the zones where the specimen's width decreases can be observed. Due to the simplified model of the material which do not include local discontinuities, further increase of stress causes plasticity in the whole tapered part of the sample.

A comparative analysis of stress-strain dependences was performed for the results obtained from laboratory tests and numerical models at the speed of testing of 10 mm/min. Fig. 12. shows the results from experiments and numerical models. In addition, the influence of strain measurement method on the results was examined. The strains were calculated in three ways (characteristic points are shown in Fig. 9):

– directly from extensometers measurement:

$$\varepsilon = \frac{\Delta_A - \Delta_B}{50}$$

– the ratio of displacements measured at machine's clamps to base length of 50 mm:

$$\varepsilon = \frac{\Delta_M}{50}$$

– the ratio of displacements measured at machine's clamps to base length of 115 mm:

$$\varepsilon = \frac{\Delta_C}{115}$$

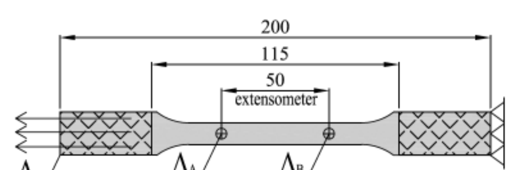

Figure 9.
Base lengths for calculation of strains

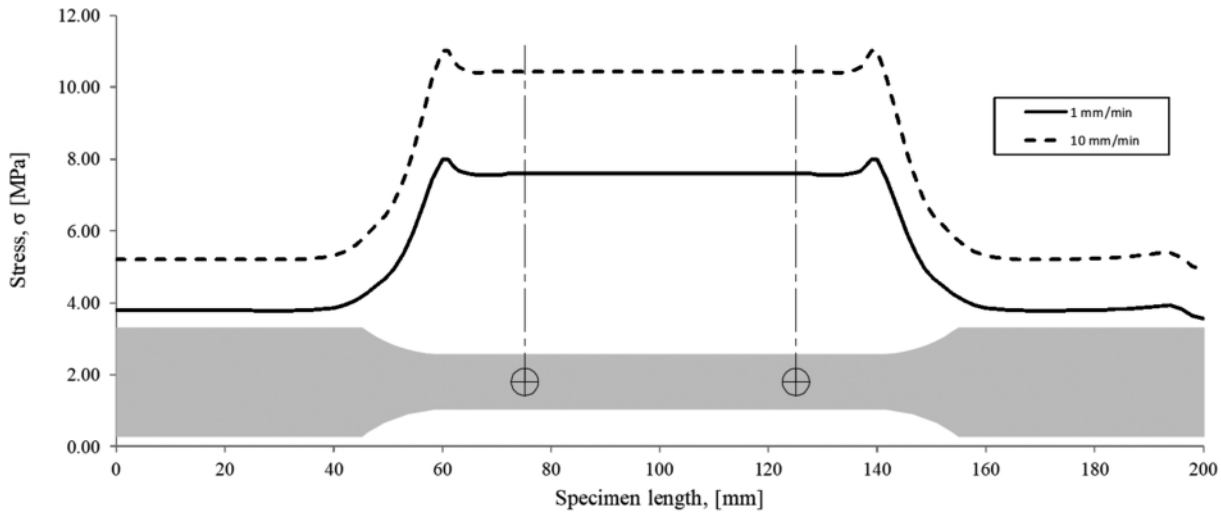

Figure 10.
Distribution of longitudinal engineer stress at the beginning of plasticization process

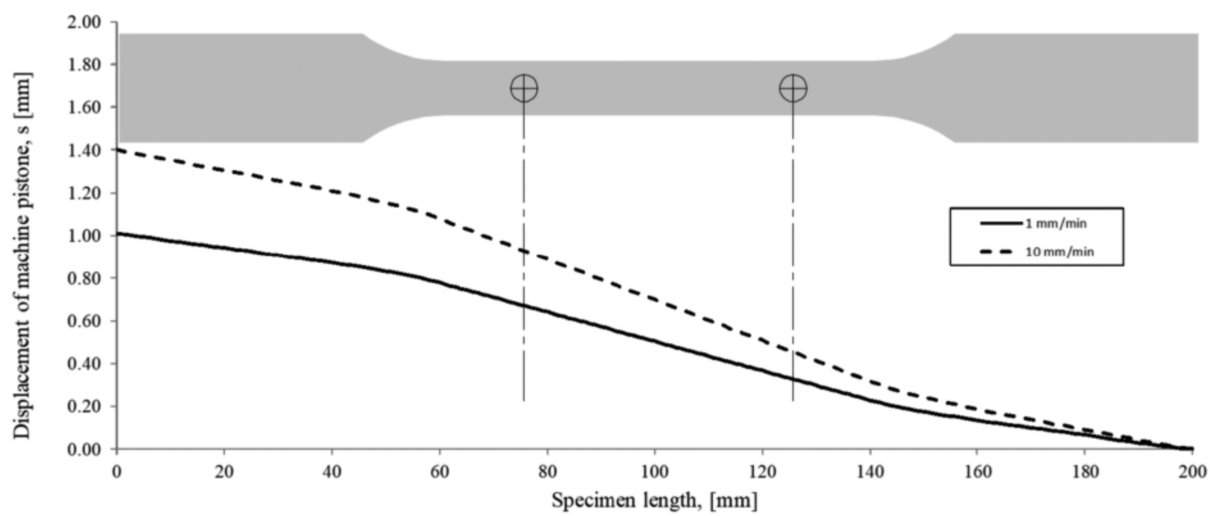

Figure 11.
Longitudinal deformation distribution at the beginning of plasticization process

The strains obtained directly from the narrowed part of the sample (using extensometers) were compared with strains obtained cross-head displacement. The model of the material assumed simulates correctly the behaviour of the material in the state of pure tension as evidenced by the plots shown in Fig. 12. There is also a noticeable difference in the results obtained depending on the strain measurement method. As can be seen, the strains obtained from extensometers (~7%) are much lower than values based on the cross-head displacement (~18%), as in the manufacturer's tests, where a 4.5-inch displacement of the clamps was referenced to a 1.5-inch tapered sample base. In turn, the results obtained for a base length of 115 mm (~8%) slightly deviate from the results from extensometers.

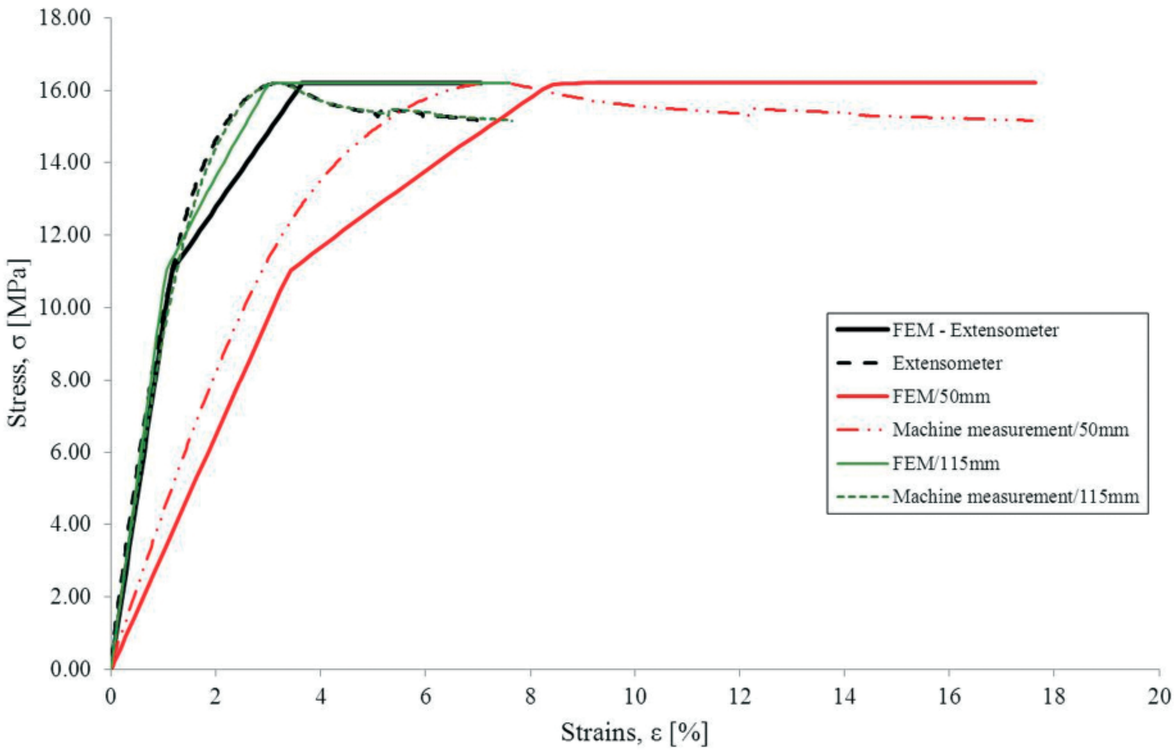

Figure 12.
Comparison of stress-strain plots obtained from numerical analyses and experiments

4. CONCLUSIONS

The paper presents results from experimental studies on the methyl methacrylate adhesive PLEXUS MA420. The tests were carried out according to standards [17, 18]. Two speed of tests were considered: 1 and 10 mm/min.

Tensile tests show the significant dependence of the results on the speed of testing. For the lower crosshead speed lower values of tensile strength and higher plastic strains at failure were observed.

According to [17] the boundary between rigid and semi-rigid plastics is expressed as a value of the modulus of elasticity of 700 MPa; therefore, the selected adhesive can be classified as a rigid material. The characteristics of MMA adhesive, regardless of the load rate, showed that there is always a certain constant section of plastic stresses what compared to most of the epoxy adhesives used in the civil engineering is a safer solution.

The moment of failure of construction in which MMA adhesive would be used probably would be preceded by visible deformation, which allows for early countermeasures.

The paper also presents the differences between the standards [16] and [17, 18] which consists primarily of determining the speed of testing and the range of strains for which Poisson's ratio should be calculated.

Numerical simulations using FEM have shown that extensometers are required for testing of adhesives. Unsymmetrical anchorage or too large base length of the extensometer may cause distortion of results due to the transition zone in the tapered part of the sample, where the first plastic deformation appears.

Strains calculated using extensometer measurements are a precise method because the section on which the displacements are measured is constant. The results obtained from displacements of the machine clamps and assumption of reference length of 115 mm coincide with the measurement of extensometer. Results compatibility was because the length of the tapered part of the sample in relation to the distance between the clamps was very large – 70%. If a smaller sample was analyzed, i.e. 5A according to [18], the results would probably not be so much convergent, as this ratio would be 50%. In the case of the assumption that the displacement of the machine measurement only refers to the length of the base 50 mm on tapered part of the specimen can lead to a significant overestimation of the strain values, which was confirmed by the analyzes. Designated for numerical analysis of specific points, such as the limit of elasticity and plasticity (summarized in Tab. 1.) have shown that, in the elastic range the secant modulus of elasticity is independent of the load rate. For speed of 1 mm/min it was 964 MPa and for 10 mm/min it was 957 MPa. Only when the stresses overcame the elastic limit, the results began to vary. For the design construction joints, different speed load increment should not significantly affect the stress distribution, provided that the analysis will be in the elastic range of adhesive.

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